ADVANCES IN TURBO ENGINE REAL-TIME SIMULATION FOR MODERN CONTROL SYSTEM DEVELOPMENT

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Abstract

The available computational power is constantly increasing. This facilitates detailed simulations of turbo engine dynamical behavior in real-time with a high sampling rate. These simulations can include secondary effects as well as failure cases.

This paper first gives an overview and a comparison of the most common simulation methods. Special real-time issues will be discussed.

Following this, examples will be given of how real-time engine simulations can be used for the development of engine control systems. One main application described is rapid prototyping of control systems for helicopter engines as performed at the Chair of Flight Propulsion. The other application described is the design of control systems including on-board engine models. The advantages of such an approach for highly integrated hypersonic engines, to be used in the lower stage of a planned two-stage-to-orbit vehicle, will be discussed.

1 Introduction

In the last years, the computer industry was able to duplicate computing power approximately every 18 months, in accordance with Moore's law. Even if this fast development pace continues and no physical limitations are reached, three dimensional CFD (Computational Fluid Dynamics) calculations of turbo engines in real-time will probably not be achievable in the near future.

Physical engine model or performance analysis model calculations, however, can be carried out in real-time today, with small time steps of approximately 10 milliseconds, using affordable computer technology [1]. This paper describes the advantages of real-time performance analysis modeling compared to traditional real-time methods like state space or function generators. Examples are given how the recent advances in computer technology allow higher modeling detail and accuracy, from which both the control design process and the control system itself benefit.

2 Real-Time Simulation

2.1 Physical Modeling

For physical modeling or performance analysis modeling of turbo engines, the propulsion system is subdivided into its different components such as: inlet, compressors, combustion chamber, turbines, thrust nozzle, etc. Each component is characterized by its distinct physical behavior, which is either described by an appropriate set of equations and/or characteristic maps. These maps can be recorded by rig tests or CFD calculations. Another possibility is to use generic maps and scale them to suit the specific application.

The simulated components are coupled via the laws of mass-, momentum- and energy conservation. This usually leads to a coupled set of non-linear equations, which can be solved numerically. Since the number of required iteration steps varies, it must be limited to ensure a deterministic calculation time for real-time systems.

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14. ABSTRACT
The available computational power is constantly increasing. This facilitates detailed simulations of turbo engine dynamical behavior in real-time with a high sampling rate. These simulations can include secondary effects as well as failure cases. This paper first gives an overview and a comparison of the most common simulation methods. Special real-time issues will be discussed. Following this, examples will be given of how real-time engine simulations can be used for the development of engine control systems. One main application described is rapid prototyping of control systems for helicopter engines as performed at the Chair of Flight Propulsion. The other application described is the design of control systems including onboard engine models. The advantages of such an approach for highly integrated hypersonic engines, to be used in the lower stage of a planned two-stage-to-orbit vehicle, will be discussed.

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The superordinated iterations needed to solve the conservation equations can be avoided by breaking the algebraic loops in the system. This can be achieved, for example, by introducing gas volumes between the engine's components [2][3]. The advantage of this non-iterative method is the more deterministic calculation time, which is crucial for real-time systems. To achieve the same results as with the iterative method, relative small simulation time steps are required. In the example case depicted in figure 1, which shows the acceleration of a two spool turbofan engine with afterburner and low bypass ratio, accurate simulations are possible when the time step is below 0.01 s. A disadvantage of the non-iterative method is that the flow of information between the engine's components must be fixed before the simulation, so the method is not very flexible with respect to changed component operating modes, for example the critical or sub-critical flow through turbines or the different operating modes of supersonic air inlets.

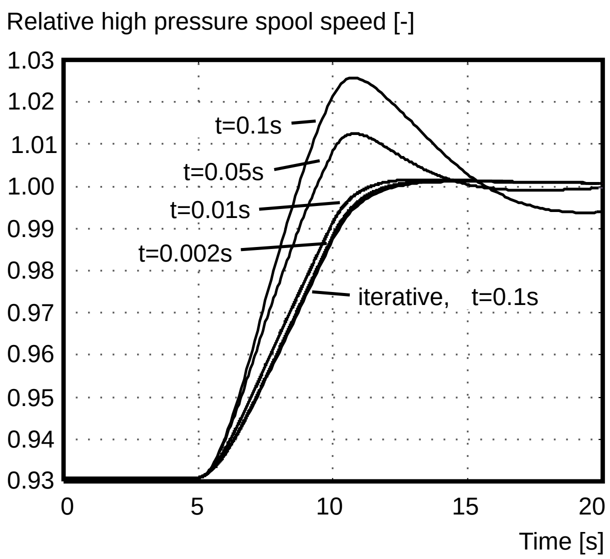

Figure 1: Non-iterative versus iterative physical modeling: acceleration of a two-spool low bypass engine

Due to the detailed thermodynamic and fluiddynamic calculations involved, physical models may need a lot of computational power to be performed in real-time using small time steps.

Future improvements in performance analysis modeling could include the replacement of the component maps used today by a more detailed physical modeling of the turbo components. For example, the compressors and turbines could be modeled with an apropriate set of equations at a blade row level.

2.2 State Space Systems

Another possibility to simulate turbo-engine behavior in real-time is to use a state space model originating from linear system theory. The engine is described by linear state and output equations

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \quad (1)$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du} \quad (2)$$

with the matrices **A**, **B**, **C** and **D** determined either by linearization of physical models or by system identification, at a specified engine operating point.

For the model to be valid throughout the flight envelope and the engine's power range, multiple linearizations must be made and the system matrices have to be interpolated between the different linearization points [4]. The matrices obtained at the specific operating points and the linear state space models valid in the vicinity of this points may also be needed for control design, since control theory is still based to a great extent on linear system theory.

The biggest advantage of state space simulations is the very fast computational speed compared to physical models and thus the possibility of using very small time steps for real-time simulations. Another advantage is the quite fixed execution time. The method is, however, less flexible than performance analysis.

2.3 Function Generators

The simulation method of function generators uses either experimental data or results from performance analysis. These data are filed in cubic splines as functions of certain parameters which determine the engine's operating condition. Parameters could be the corrected gas generator speed and the flight Mach number, for example.

The transient engine behavior can be represented by another set of linearized functions over the relative change in fuel flow, which is

usually the reason for a dynamic change of state. As with state space systems, the increase in calculation speed of this method is set off by a loss of flexibility.

2.4 Comparison of Different Simulation Methods

A first criterion for a comparison of the simulation methods described above is the accuracy compared to experimental data of turbo engines. If state space and function generators models are derived from a physical engine model, it is apparent that they can best achieve the same accuracy than the underlying physical model. Generally speaking all three methods can achieve an accuracy of about 2% full scale with some amount of adjustment necessary.

When looking at the execution time, the advantage lies clearly on the side of state space or function generator methods which are orders of magnitude faster than equivalent performance analysis models.

The most stable simulation method is function generators, followed by non-linear (including interpolated system matrices) state space models and physical models. With physical modeling in real-time, care must be taken that no circumstances during the simulation can lead to software exceptions.

Another important criterion is the flexibility of the method with respect to changes in modeling or changes made in the design of the turbo engine to be simulated. Due to its modular design, the physical performance analysis can be adapted much faster than the models using the other two methods.

When looking at how the different methods scale with respect to the complexity of the engine to be modeled, performance analysis models are clearly superior. Both state space and function generators simulations get quite complicated when the engine process is complex, for example in a variable cycle engine (VCE), or when numerous non-linearities of the turbo engine or the operating conditions must be taken into account.

Performance models also score when the criterion is the availability of the model. Performance models today are available at the respective engine manufacturers at an early stage in the engine's design process. The same models that are used for performance calculations during the turbo engine design could also be used in the control design process, using a common data base making design changes easier. However, there may always be the need for linear state space models for control design purposes, but these can be obtained from automated linearizations of the physical performance model at certain operating points.

To sum up, if enough computing power is available, it is desirable to use physical engine models wherever possible. At the Chair of Flight Propulsion, physical models are used through most of the control design process, and if linearized models in the form of state space matrices are needed, they can be generated automatically out of these physical models.

2.5 Real-Time Aspects

If the necessary computing power is available for the desired time resolution, real-time simulations can be carried out using complete physical modeling. For example, the detailed simulation of a hypersonic airbreathing engine, proposed for a future German space transportation system [6], is carried out at the Chair of Flight Propulsion within the German Special Research Program (SFB 255). This engine simulation can be evaluated in real-time on a Pentium II-300MHz system with time steps below 10 ms, which equals a simulation frequency of 100 Hz. The simulation includes the physical modeling of the hypersonic inlet including detailed shock wave modeling, the turbo-engine with its compressors and turbines described by component maps, the mixer and afterburner, as well as the single expansion ramp nozzle (SERN) described by a characteristic map. The distribution of calculation time between the engine's components is shown in figure 2. It can be seen that the complex shock calculations in the hypersonic inlet take up more than half of the overall calculation time.

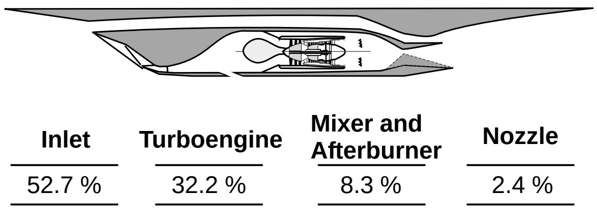

Figure 2: Distribution of calculation time between the different components of an engine for a proposed two-stage-to-orbit vehicle

When looking at the calculation times of the turbo engine itself, the biggest amount of computing power is used in the compressor and turbine routines (see figure 3).

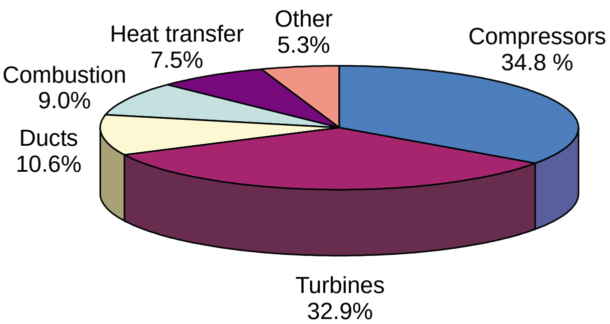

Figure 3: Distribution of calculation time within the turbo engine part

Taking a look at the calculation time that is spent in different software subroutines, it can be observed that 53 % of the overall time is spent calculating static pressures and temperatures out of the total quantities. This time can be greatly reduced by using intelligent initial guess values for these calculations. 38 % of the overall computational time is used to evaluate polynomials that describe the thermodynamic properties of the gases. This calculation time cannot be reduced by using convenient look-up tables and interpolations instead of the polynomial calculations.

A problem when using performance analysis models in real-time is the determination of the execution time. When using performance analysis with superordinated iterations to solve the equations of conservation, it cannot be determined after how many iterative steps the solution will converge, i.e. all compatibility errors will be below a given margin. This problem can be overcome by limiting the number of iterations, regardless of the error remaining, or by using the non-iterative method described in chapter 2.1. However, also if using this method, due to the subordinated iterations needed in thermodynamic and fluid dynamical subroutines, care must be taken that the maximum calculation time for one time step is in any case low enough for the desired simulation frequency.

2.6 Modeling of Secondary Effects and Failures

Performance analysis also facilitates modeling of so-called secondary effects, for instance the impact of the complex tip clearance effects on turbo-machinery behavior during transients. Due to the detailed heat transfer modeling necessary, a lot of computing power is needed to carry out such calculations in real-time with a sufficient time resolution.

Using performance modeling, it is also possible to test control designs or even control hardware under abnormal or failure conditions. Compressors, for example, are quite sensitive to inhomogeneous flow fields, also known as compressor distortion. With a physical model, it is possible to simulate the reaction of the turbo-engine plus control system to a compressor distortion, using the "parallel compressors" [5] simulation technique.

In super- or hypersonic flight, the variation of the thrust vector angle in different failure cases is of imminent importance. Figure 4 shows the simulated change in thrust vector absolute value and angle for the two-stage-to-orbit vehicle studied at the Chair of Flight Propulsion within the SFB 255. This vehicle is propelled by five combination (turbo engine and ramjet) engines [6][7]. Depicted is the normal operation, a combustion flame-out failure and a case where, due to an actuator failure, the inlet operates in a choked condition. An immense variation of both the absolute value and the angle of the thrust vector can be observed. With these simulations, the reactions of the control system to failures can be studied and it can be investigated if the maneuverability of the hypersonic transport plane can nevertheless be maintained.

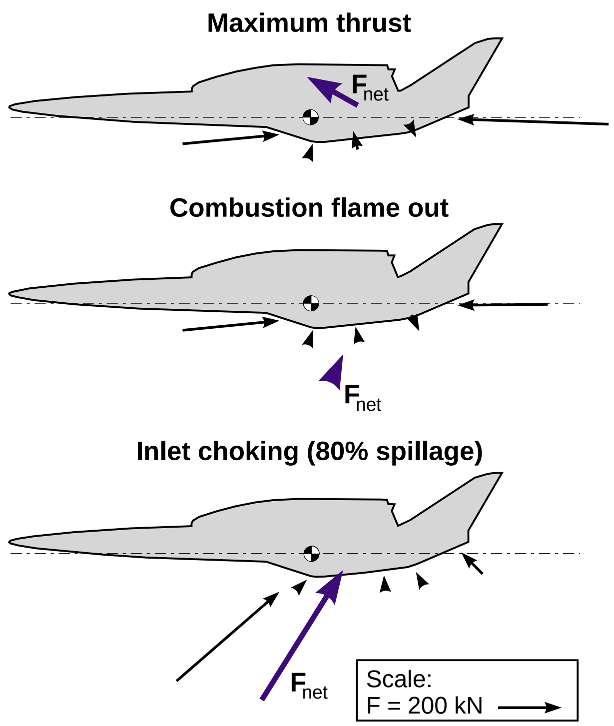

Figure 4: Thrust vector variation (bookkeeping) of a two-stage-to-orbit vehicle's lower stage due to failures

3 Integrated Development Environment

The following chapter gives an overview of the integrated software environment used at the Chair of Flight Propulsion. The software is used, as mentioned above, for the numerical simulation of hypersonic engines as well as for experimental research work carried out at the chair's helicopter engine test bed. As described in the previous chapters, the quality and also the availability of an up-to-date engine model is crucial to an efficient control system development process. Baseline for all simulation models is the chair's flexible performance analysis program (PSSD) written in C. The program consists of various modules that can be combined as needed for the application. The modules can be divided into the following groups:

- Thermodynamic routines for various gases (air, hydrogen, etc.)
- Fluidmechanics
- Heat transfer
- Turbo engine components (inlets, ducts, compressors, turbines, mixers)
- Solvers (iterative, non-iterative)
- Interfaces (input/output formats: ASCII, MATLAB, TCP/IP)
- Mathematics (matrix manipulation, linearization)

The performance program can be easily configured to satisfy the need of the user in the different stages of the design process. Important for the efficient use of the program is a wide range of interfaces to accept inputs from and provide outputs to other applications. Integrated into the program is, among various file formats (ASCII, MATLAB) also a TCP/IP-interface that allows the communication with external applications such as LabVIEW or MATLAB/Simulink. The network data handling requires only little computational power and allows the distribution of tasks to remote CPUs, e.g. a graphical real-time display of the simulation results, while conserving the host's CPU-power for the simulation.

Another valuable possibility is the synchronization of the performance synthesis model with an offline simulation in Simulink during the control law design.

The TCP/IP-link also offers the integration of an sophisticated real-time synthesis engine model into flight simulators, thus contributing to a more realistic overall simulation result.

A very interesting option realized is the link-up between the engine-model and the data acquisition system of the engine test cell. This allows the simulation of experiments and the verification of the test facilities in the advent of an engine run.

For on-board engine models, the limited computational power restricts the use of performance synthesis models. Alternatively, as described in chapter 2.2, linear or non-linear state space models are commonly used. To ensure the actuality of the state space models, a routine of the performance calculation program automatically linearizes the engine model and produces matrices that are immediately available in MATLAB/Simulink for simulation or control law design. With this feature, it is granted that different members of integrated development teams always use consistent engine models.

4 Rapid Prototyping of Control Systems

Driven by the need of shorter development times, the development effort of control systems can be drastically reduced by applying the principles of rapid prototyping. These principles base on an integrated hard- and software approach to relief the design engineer of routine tasks. With MATLAB as basic numerical tool, the design of control laws using appropriate tools can be quickly done. Using the graphical programming extension Simulink, the entire control system software can be developed and tested offline. For verification at this stage, either test data from previous test runs or, through a TCP/IP interface, a performance synthesis model of actuators, turbo engine and sensors are available. Once the control software has been successfully tested offline, an automatic code generation process is invoked. The control laws, designed graphically in Simulink, are translated into C and with the means of a cross-compiler downloaded onto the real-time hardware. The hardware can be either the flight approved hardware or a special experimental real-time system. The system shown in figure 5 is a multi-processor platform consisting of a DEC alpha-CPU and a TI C40 digital signal processor. It provides very high computational power for sophisticated control algorithms. With the recent advances in computer technology, comparable computing power should be available for on-board systems within the foreseeable future. The automatic code generation drastically reduces the engineers' workload and improves the reliability of the code, since typical human errors like typing-errors etc. are avoided. The quality of the code supplied by the latest generation of code generators, in terms of speed and memory usage, equals handwritten code.

With the real-time application automatically generated, the hardware can be connected to a real-time simulation model of the test bed engine, which typically consists of a synthesis performance model with appropriate input and output interfaces to connect to the control system hardware. With this hardware-in-the-loop simulation (HIL), the controller's real-time behavior can be tested. Also, at this stage the user interfaces of the control system (eg. switches, levers, panels etc.) can be checked for their functionality and the entire planned rig test can be simulated.

Once this step is successfully passed, the control software can be validated with the test bed engine. For the following experiment, no further changes to the control system other than disconnecting the simulator and connecting the engine signals are required.

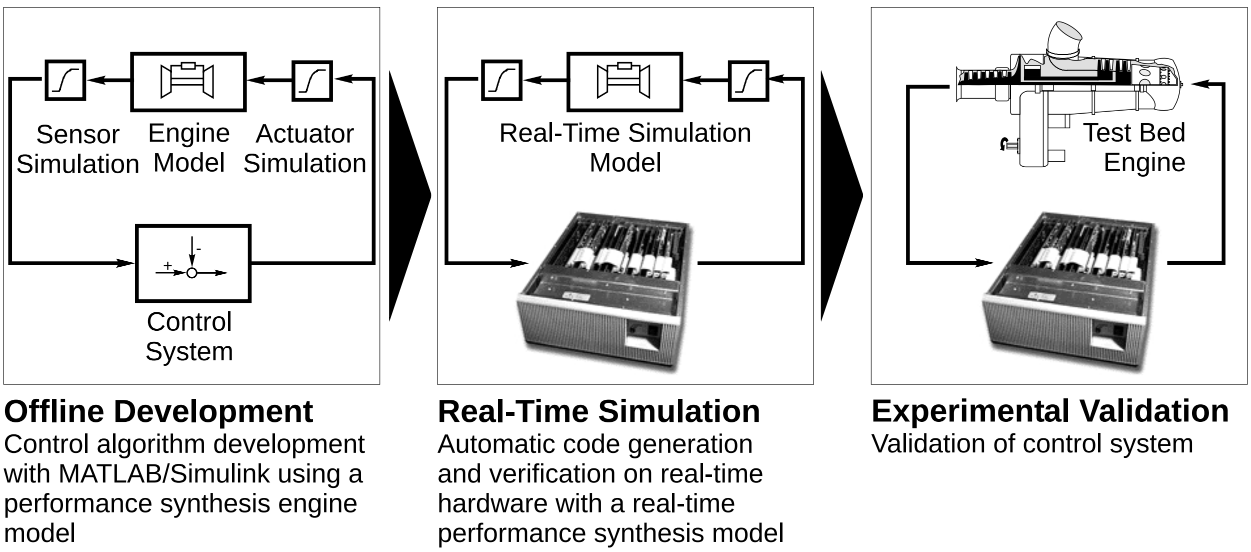

Figure 5: Software development process (rapid prototyping) of control systems for helicopter engines

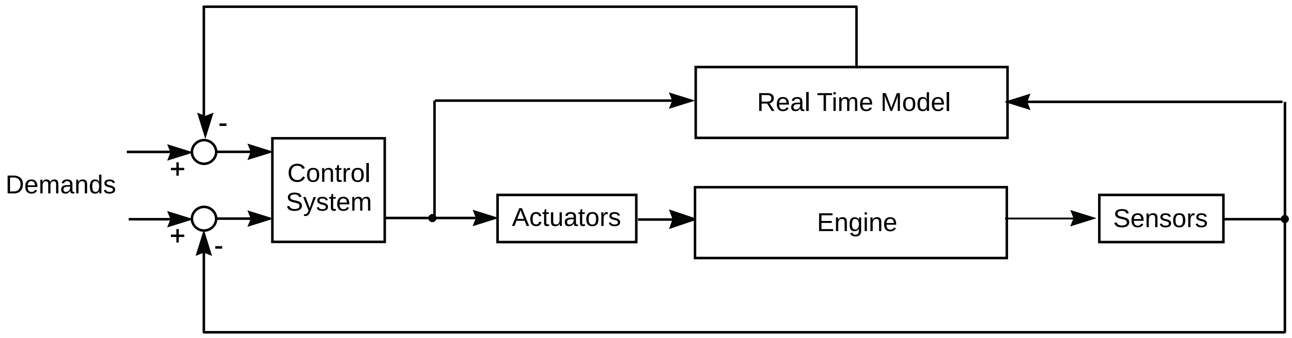

Figure 6: Integration of engine, on-board model and control system for model based control

5 Model Integrated Control Systems

Another possibility provided by real-time engine simulations is the direct use of an on-board model in the control system itself.

This on-board model, running at a high sampling rate of approximately 10 ms, can provide the control system with information that cannot be determined by engine sensors (refer figure 6). This could include, for instance, the high pressure turbine inlet (or blade, depending on the degree of detail of the engine's modeling) temperature that is usually too high to measure using widely available sensor technology. Another example could be the surge margins of the engine's compressors, which cannot be measured but are very crucial for a safe engine operation.

Especially in supersonic and hypersonic flight, the matching between the air inlet of the vehicle and the engine is of inherent importance. The procedure commonly used today is a separate design of engine and inlet control systems. An integrated approach, however, could lead to a better synchronization of the mass flow delivered by the intake and the mass flow demanded by the engine and thus improve both safety and performance. During hypersonic flight, an on-board model could provide detailed, real-time, information about the system of oblique and normal shock waves in the inlet to the control system and thus allow an accurate positioning of the final normal shock wave. Figure 7 shows a comparison between a one-dimensional, real-time, simulation of an unstarted hypersonic inlet, as integrated in the engine model shown in figure 2, and 2-dimensional CFD calculations. With this inlet real-time model on board, the shock positions and Mach numbers could be used by the control system to minimize total pressure losses and the risk of an inlet unstart during hypersonic flight.

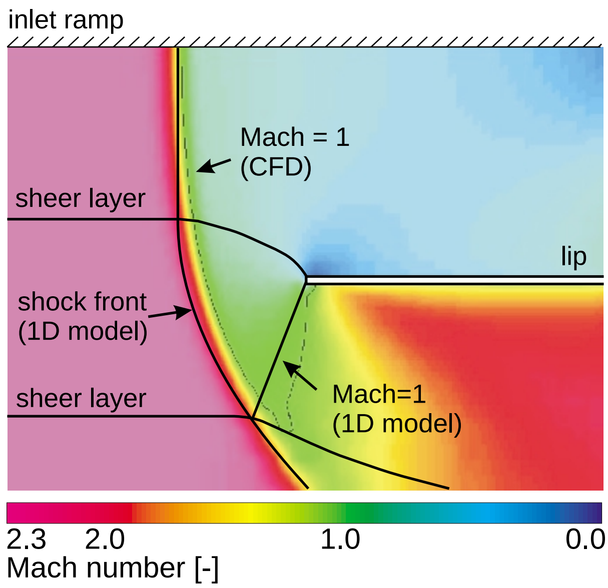

Figure 7: Comparison real-time model / CFD calculations of a two-stage-to-orbit vehicle's unstarted inlet

5.1 Engine / Simulation Matching

Real-time turbo engine simulations can be matched with an actual engine in a way that the simulation errors in thermodynamic variables (temperatures, pressures, mass flow) do not exceed 2% full scale. The question arises, however, what happens if certain engine parameters like component health parameters, for instance, degrade due to aging or damage. The consideration of changing engine parameters, which could be the cause of significant differences between simulated and actual engine variables, indicates the need of some kind of model

tracking algorithm that is able to compensate for theses parameter changes.

For a systematic approach to the given task, it is first necessary to carry out a sensitivity analysis to determine the parameters that are most crucial for the simulated engine variables to be used in the control system. After this, an algorithm has to be set up that allows an on-board identification of these parameters.

5.2 Non-linear Observers

One possibility to identify the engine's parameter changes is to use the on-board model as a non-linear state observer [8]. State observers are originally used to determine non-measurable state variables of dynamic systems from known measurement and input variables, to make them available for state feedback controllers. There is, however, the possibility to treat parameters which shall be identified as additional states of the dynamic system. This adds dimensions to the system's state space. To be able to use this approach, the extended system (original system states plus additional "parameter" states) has to be observable using the available measurements [9]. If this is the case, an observer gain matrix can be shaped using either pole placement or optimum filter (Kalman filter) methods. A tradeoff between identification speed and sensor noise sensitivity has to be made during the gain design.

The overall setup of the on-board model running as non-linear state observer is shown in figure 8. It can be seen that the estimation error, **y-•** , is fed back into the real time simulation through the gain matrix **L.** The resulting signal changes the system states and the parameters to match the engine states **x**. If the identified parameters are physical, they may also be used for monitoring purposes.

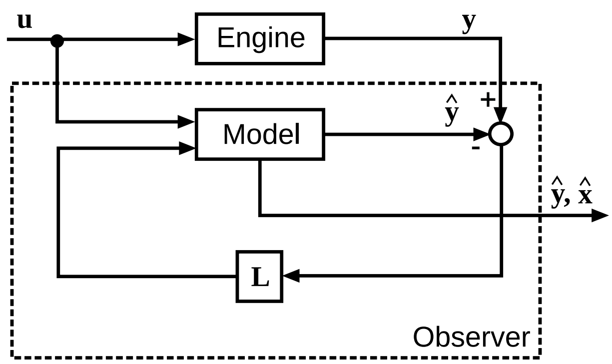

Figure 8: On-board model, implemented as non-linear observer

An example simulation of a non-linear model implemented as observer is plotted in figures 9 and 10. Figure 9 shows a step change in an engine health parameter leading to a change in high pressure spool speed (refer figure 10). It can be seen how the observer model changes the parameter to match the spool speed output. The identification is achieved after 4 s in this example [10].

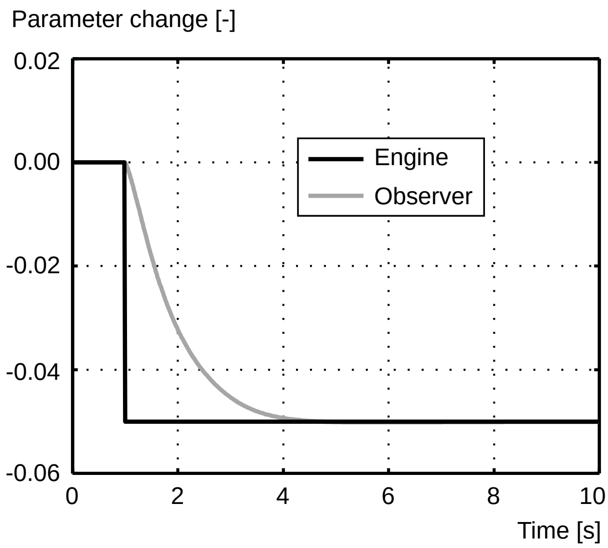

Figure 9: Identification of a changed engine parameter using a physical model as non-linear observer

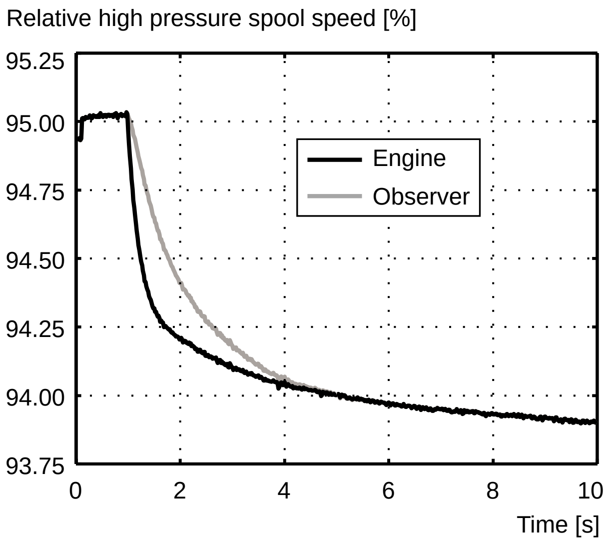

Figure 10: Matching of the high pressure spool speed during the identification process

6 Conclusion

Due to the growing available computational power, real-time simulations of dynamic turbo engine behavior can be carried out using performance analysis modeling.

This partly removes the need for state space or function generator modeling and facilitates one common engine model to be used during engine design, engine control system design and hardware-in-the-loop verifications, allowing faster design changes. Even if state space modeling is needed, for example during the control design process, these models can be derived from the performance analysis model using automated generation processes.

But performance analysis models cannot only be useful during the control design process but could also play an important role as on-board models in future engine control systems. If an on-board model can be properly matched with the real engine, it can provide the engine control system with valuable information about the engine's current dynamical state. This information can also be very useful for engine health monitoring purposes.

This paper showed two applications of real-time engine models and gave an outlook how future control design and development processes can benefit from more detailed simulations. The degree of detail in the engine models will increase with the computational power available, facilitating more accurate and faster turbo engine simulations, including various types of secondary effects and failure simulations.

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